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Can gardeners identify 'future invaders'?

Tomos Siôn Jones[1], Alastair Culham[1], Brian John Pickles[1], John David[2]

1 *School of Biological Sciences, University of Reading, Reading, UK* **2** *Royal Horticultural Society, RHS Garden Wisley, Woking, UK*

Corresponding author: Tomos Siôn Jones (ae1666@coventry.ac.uk)

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Abstract

It is estimated that there are 30 million gardeners in Britain, who could play a crucial role in being the 'first contact' for reporting ornamental plants in gardens with invasive potential. Invasive species are one of the five drivers of the global nature crisis, many of which were originally introduced through ornamental horticulture. Ornamentals confined to gardens and those which have already naturalised, but are not yet shown to be invasive, represent a 'pool' of species with invasive potential – 'future invaders'. An online survey asking gardeners to report ornamentals they had noticed invading or taking over their garden resulted in 251 different taxa being reported (including cultivars). The future invaders were prioritised with a simple yet structured scheme, looking at the domestic and global naturalised and invasive status of each taxon, including in the Global Register of Introduced and Invasive Species (GRIIS) and the Global Naturalized Alien Flora (GloNAF) databases. The structured scheme identified a shortlist of nine ornamentals of concern which should be prioritised for further analysis, such as a formal risk assessment. Identifying and preventing future invaders before they escape gardens is critical, to prevent future threats to nature. There is also a gap in the identification of potentially invasive ornamentals, which are not currently invasive, yet are beyond the scope of formal horizon scanning because they are naturalised. Here we explore whether surveying gardeners can be a suitable approach to prioritising future invaders while also being an opportunity to increase awareness of invasive species. This positive feedback loop between gardeners and invasion scientists could help reduce the risk of future invaders.

Keywords

Invasive plant species, invasive potential, online survey, ornamental horticulture, public engagement

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Introduction

In Britain and Ireland, non-native (*sensu* Macpherson et al. 1996) plants now constitute over half of the wild flora (Stroh et al. 2023). Similarly, at least 75% of the naturalised flora globally is thought to have escaped domestic gardens (van Kleunen et al. 2018). There is also a continued increase in plant introductions (first record rate) globally (Roy et al. 2012, Seebens et al. 2017). This is projected to result in an increase in the number of naturalised species particularly in Europe (Seebens et al. 2021). Although the main introduction pathway or source of invasive species globally is ornamental horticulture (Drew et al. 2010; Dehnen-Schmutz 2011; Hulme et al. 2017; van Kleunen et al. 2018; Arianoutsou et al. 2021), only a relatively small number have so far become invasive (Stace and Crawley 2015). Invasive species threaten native biodiversity (IUCN 2000) and/or have economic, human health, or quality of life impacts (IPBES 2019) and have cost the UK economy between £5.4 and £13.7 billion since 1976 (Cuthbert et al. 2021). Garden ornamentals (Cubey et al. 2022) confined to gardens and those which have already naturalised, but not yet shown to be invasive, represent a 'pool' of species with invasive potential – 'future invaders' *sensu* Mayer et al. (2017) – or an invasion debt (Essl et al. 2011; Haeuser et al. 2018).

Despite the risks of invasive species and future invaders, ornamental horticulture brings with it many benefits such as to human health (e.g. Hoyle 2021) and by providing ecosystem services (e.g. Salisbury et al. 2015, 2017). The ornamental horticulture and landscaping industry also contributed (e.g. through retail and production of ornamentals) £28.8 billion to UK GDP in 2019 with a potential increase to £41.8 billion by 2030 (Ornamental Horticulture Roundtable Group 2021).

Hence, identifying and preventing future invaders before they escape gardens is critical, both ecologically and economically, and gardeners may have a key role in this. Here we explore whether surveying gardeners can be a suitable approach to prioritising future invaders.

How do ornamentals escape, and become invasive?

Numerous frameworks have been developed to better understand why certain species become invasive and to improve links between invasion science, policy and management (Wilson et al. 2020). One example is the Unified Framework for Biological Invasions (Blackburn et al. 2011), referred to here as the 'unified framework'. This combines the concepts of stages (Williamson 1996; Williamson and Fitter 1996) and barriers (Richardson et al. 2000) in invasion science (Wilson et al. 2020). Barriers can be described as limiting factors that restrict a species from 'succeeding' to the next stage. The unified framework is arguably the most applicable framework for ornamental horticulture because it recognises human-imposed cultivation barriers (e.g. garden fences) between introduction and naturalisation. Blackburn et al. (2011) recognise that it is possible for species to 'skip' this barrier if introduced directly into the wild unintentionally. However, there is no recognition that this barrier can also be 'skipped'

due to intentional introduction into the wild *sensu* Roy et al. (2014). Note that the unified framework of Blackburn et al. (2011) does not incorporate the impact of an invasive species. The stages of the invasion process are not independent of each other. For example, Milbau and Stout (2008) found that an early first record in the wild was one of the factors increasing the likelihood of a non-native plant transitioning from being a casual to being naturalised. One factor important in this specific context of ornamental horticulture is hybridisation which can increase the invasive potential of ornamentals and is linked with climate change (Kohn et al. 2009; Klonner et al. 2017).

Can gardeners identify potentially invasive ornamentals?

Gardeners have a crucial role in reducing the risks associated with invasive species, including at a practical level, for example through their choice of ornamentals to grow and steps to adopt while gardening to limit the spread of invasive species into the wild (Jones et al. 2024). Gardeners also have a role in identifying ornamentals with invasive potential because they often have expert knowledge (Dehnen-Schmutz and Conroy 2018) of how different ornamentals are performing in their garden including those showing 'invasive behaviour'. This expert knowledge can help identify a potentially invasive species early (e.g. before escaping gardens) which is both ecologically and economically advantageous (Hulme 2006) as it allows for prevention as a management approach. It is also important to prioritise species for control (Shackelford et al. 2013; Head et al. 2015). For ornamentals, this means identifying which of the around 70,000 plants available for gardeners (Cubey et al. 2022) have invasive potential, before escaping from gardens. There are also many non-native (*sensu* Macpherson et al. 1996) ornamentals which are not currently invasive (Stace and Crawley 2015) but are beyond the scope of horizon scanning because they are already present in the wild (Roy et al. 2019) either as: i) casuals: plants surviving in the wild (i.e. outside of cultivation) due to repeated introductions; ii) survivors: plants that are persistent in an area simply due to longevity but do not reproduce; or iii) having naturalised (syn. established): a plant which is self-reproducing or increasing year-to-year by sexual or vegetative means (Stace and Crawley 2015). This leaves a gap – as identified by Dehnen-Schmutz (2011) – in the identification of potentially invasive ornamentals. This gap can be addressed by looking at 'non-invasiveness' to determine green lists (Dehnen-Schmutz 2011) or engaging with gardeners to identify potentially invasive ornamentals. The latter is the focus of this study.

Dehnen-Schmutz and Conroy (2018) tested a citizen science approach using an online survey to identify potentially invasive ornamentals (Johnson et al. 2020) and reported the naturalisation status of 121 species (including 17 native species). Eight species were not known to have escaped gardens, i.e., with no naturalised records in Britain at the time of their study. Since the Dehnen-Schmutz and Conroy (2018) study, a long-term citizen science project called Plant Alert has been launched – led by the Botanical Society of Britain and Ireland (BSBI) and Coventry University – to monitor potentially invasive ornamentals, asking gardeners to record invasive plants

in their garden (Plant Alert 2023). Such data can be used, for example, in risk assessments and for advising gardeners (Webb 2020). A survey can also act as an educational mechanism for gardeners (Reichard and White 2001; Hulme et al. 2017).

The challenge is identifying which ornamentals could become invasive in the future, not just naturalisation status. An important aspect is therefore to also look at invasive status elsewhere in the world. In this study, we identify gardeners as the target audience for engagement to identifying future invaders, i.e., species invasive potential. This has great potential for achieving Target 6 of the Kunming-Montreal Global Biodiversity Framework (CBD 2022). A structured scheme for prioritising future invaders reported by gardeners is shown below (Fig. 1).

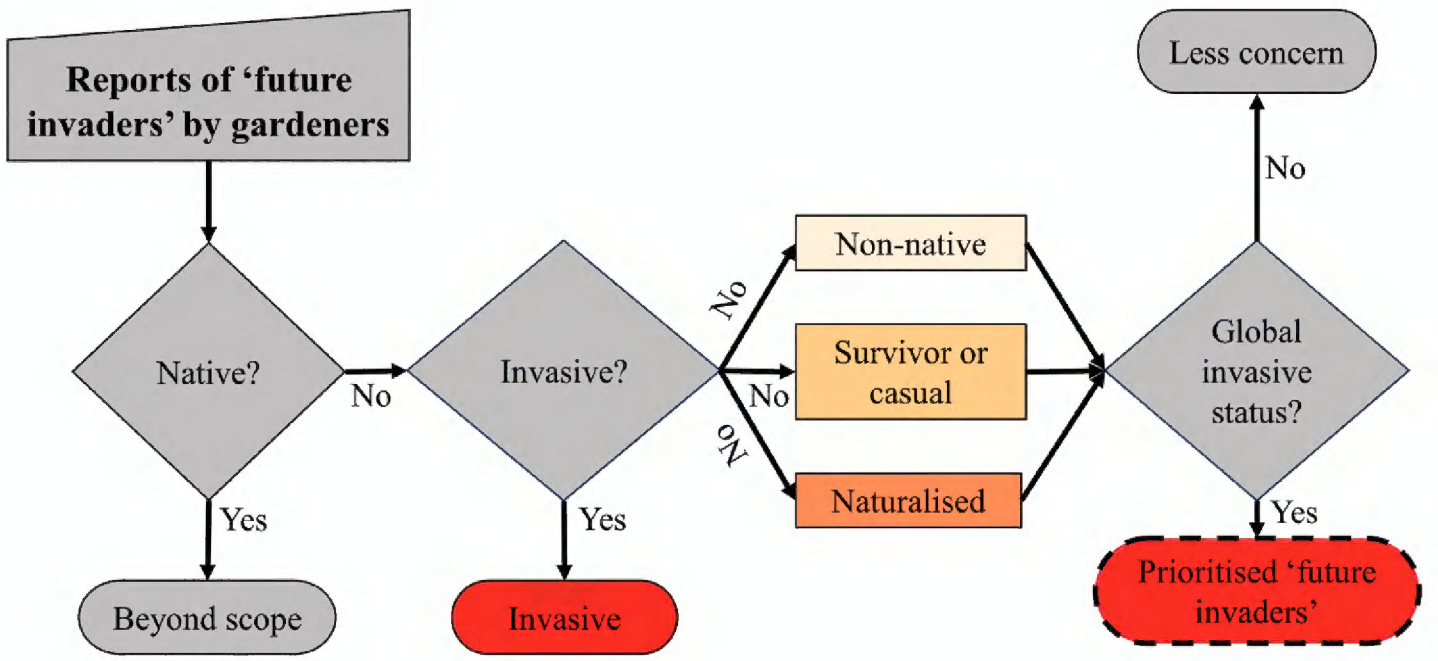

Figure 1. A structured scheme for prioritising future invaders.

This structured scheme for prioritising can be adapted depending on data and geographic scale. See Methods section for list of data sources.

We engaged with gardeners to address the research question: can gardeners identify future invaders? By doing so, we aimed to explore whether surveying gardeners can be a suitable approach to prioritising future invaders in Britain and Ireland.

Methods

Two complementary surveys were designed and conducted, which differed in their method of participation, but had the same target audience (Tweddle et al. 2012; Varner 2014) of gardeners (amateur or professionals) in Britain and Ireland. Both surveys were hosted by Jisc Online Surveys (www.onlinesurveys.ac.uk) and passed ethical review prior to implementation. Neither survey offered a comprehensive explanation of the term 'invasive' to participants because: 1) doing so might not match how gardeners use

the term in their gardens, see Jones et al. (2024); and 2) the purpose of the study was not to ask gardeners what ornamentals are having an impact in the wild (as invasive species *sensu stricto*) but rather those showing 'invasive behaviour' in gardens.

Scoping survey

A scoping survey asked gardeners to: *'list up to three ornamental plants you've noticed invading/taking over your garden'*. Participants could report up to three plants (the first being the most invasive) and the first part of their postcode (UK) or Eircode in Ireland meaning no personal data was collected. See Suppl. material 1. The survey was launched in August 2018 using the RHS's social media Twitter account (@The_RHS with 159,000 followers at the time). It was also publicised elsewhere including the November issue of The Garden (RHS 2018a), with a circulation of over 510,000 (RHS 2018b), and The Hardy Plant Society's Newsletter and the RHS's December email circulation, reaching 183,306 RHS members. Targeting existing gardening groups such as this can be effective (Tweddle et al. 2012) in recruiting participants through non-probability convenience sampling (Callegaro et al. 2015; Vehovar and Manfreda 2017). The scoping survey closed on May 19th 2019.

Chelsea survey

The scoping survey informed a follow-up survey (henceforth the Chelsea survey) which was launched at the RHS Chelsea Flower Show (RHS Chelsea) in London May 20th–25th 2019. The Chelsea survey was tested with potential participants beforehand, using regular gardening volunteers from the Friends of the Harris Garden, at the University of Reading. Minor improvements were made to the survey as a result. The Chelsea survey was approved by the Ethics Committee of the School of Biological Sciences at the University (reference number SBS18-19 36).

Relevant to this study is the question: *'what is the main ornamental plant you have noticed invading or taking over your garden?'*. This was a drop-down question consisting of the ten most reported ornamentals (based on preliminary analysis) in the scoping survey. Four of the drop-down options were for genera only which then prompted an additional question asking the participant if they could specify which species and/or cultivar. Participants could also select 'other' to report a different ornamental. See Suppl. material 1. The question could be repeated up to two times. Visitors at Chelsea who had indicated that they wished to participate at a later date were emailed with a direct link. The Chelsea survey closed in December 2019.

Data cleaning

To ensure participants of both surveys were from Britain or Ireland, the postcodes or Eircodes were geolocated using www.geocode.xyz. Responses which could not be geocoded were discarded. The plants reported in both surveys were then taxonomically

standardised in three steps: 1) manually correcting spelling errors and giving scientific names to vernacular names. This was done through expert judgement and checking RHS references (RHS 2008, 2020; Cubey et al. 2018, 2020). 'Japanese anemone' *sensu lato* is treated here as *Anemone* × *hybrida* Paxton. Any reports with a vernacular name which could not confidently be assigned a scientific name were discarded; 2) the scientific names were checked using the Global Names Resolver (gnr_resolve) function as part of the taxize package (Chamberlain and Szöcs 2013) in R version 4.0.4 (R Core Team 2021). The data source was the International Plant Names Index (IPNI 2020). The nomenclature thus follows IPNI, except for infra-specific (including cultivars) and inter-specific taxa (hybrids); and 3) infra- and inter-specific examples checked against the aforementioned RHS references, but the nomenclature to species level still follows IPNI. The standardised list was checked for duplicates and reports which were only at genus level were removed, i.e. species, subspecies and varieties as well as hybrid taxa were retained and analysed as such (except for cultivars). Native taxa (Morais and Reichard 2018; Pagad et al. 2018, 2022) as listed by Stace (2010), were also removed. Data cleaning resulted in 318 responses being discarded – including responses from the Republic of Ireland or Northern Ireland which could not be geolocated – out of the total 876 responses (562 in the scoping survey and 314 in the Chelsea survey).

Data analysis

Global and domestic invasive status (i.e. evidence of impact) was taken from the Country Compendium version 1.0 of the Global Register of Introduced and Invasive Species (GRIIS) (Pagad et al. 2018, 2022). Stace and Crawley (2015) and The Global Naturalized Alien Flora (GloNAF) database (van Kleunen et al. 2015; Pyšek et al. 2017) were used for determining domestic status, including naturalisation. The point of the study is not to make a direct comparison with Plant Alert (2023) because the questions are different but both share the principle of identifying potentially invasive ornamentals. We have therefore added the respective number of reports via Plant Alert (BSBI 2023; Plant Alert 2023) into Table 1 for context with what has been done since the data of this study was collected. Species richness of reported species (Pergl et al. 2016) and the completeness of the sampling strategy ("sample coverage", Chao and Jost 2012) were investigated using iNEXT (Chao et al. 2014, 2022; Hsieh et al. 2016). Briefly, the sampling-unit-based incidence data approach was used for interpolation and extrapolation, treating each gardener as the sampling unit, based on the gardener's expert knowledge, and the identity of their reported species as incidence data. Here we assume that while every garden has a different size and overall combination of species, each gardener accurately assessed the identity of plants that were 'invasive' within their own garden. In this approach "sample coverage" is the proportion of overall species occurrences that can be attributed to identified taxa. For the purposes of these analyses: i) cultivars were not included; and ii) observations of varieties and subspecies for which the species was already present in the dataset were combined with the observations of their respective species.

Results

The cleaned results for both surveys are presented here together with 847 reports from 558 gardeners (Fig. 2). The 847 reports included: 203 species, 8 infra-specific (4 sub-species and 4 varieties), and 13 hybrids, totalling 224 taxa. There were also 27 named cultivars resulting in 251 different taxa being reported.

Based on the 221 unique species and hybrids (see Methods section) included in the overall dataset, interpolated species accumulation of reported taxa for the survey data did not approach an asymptote (Fig. 3). For observed data the estimated 95% CI of species richness was 203.83–238.17 species (Fig. 3a, c) and sample coverage (SC) was

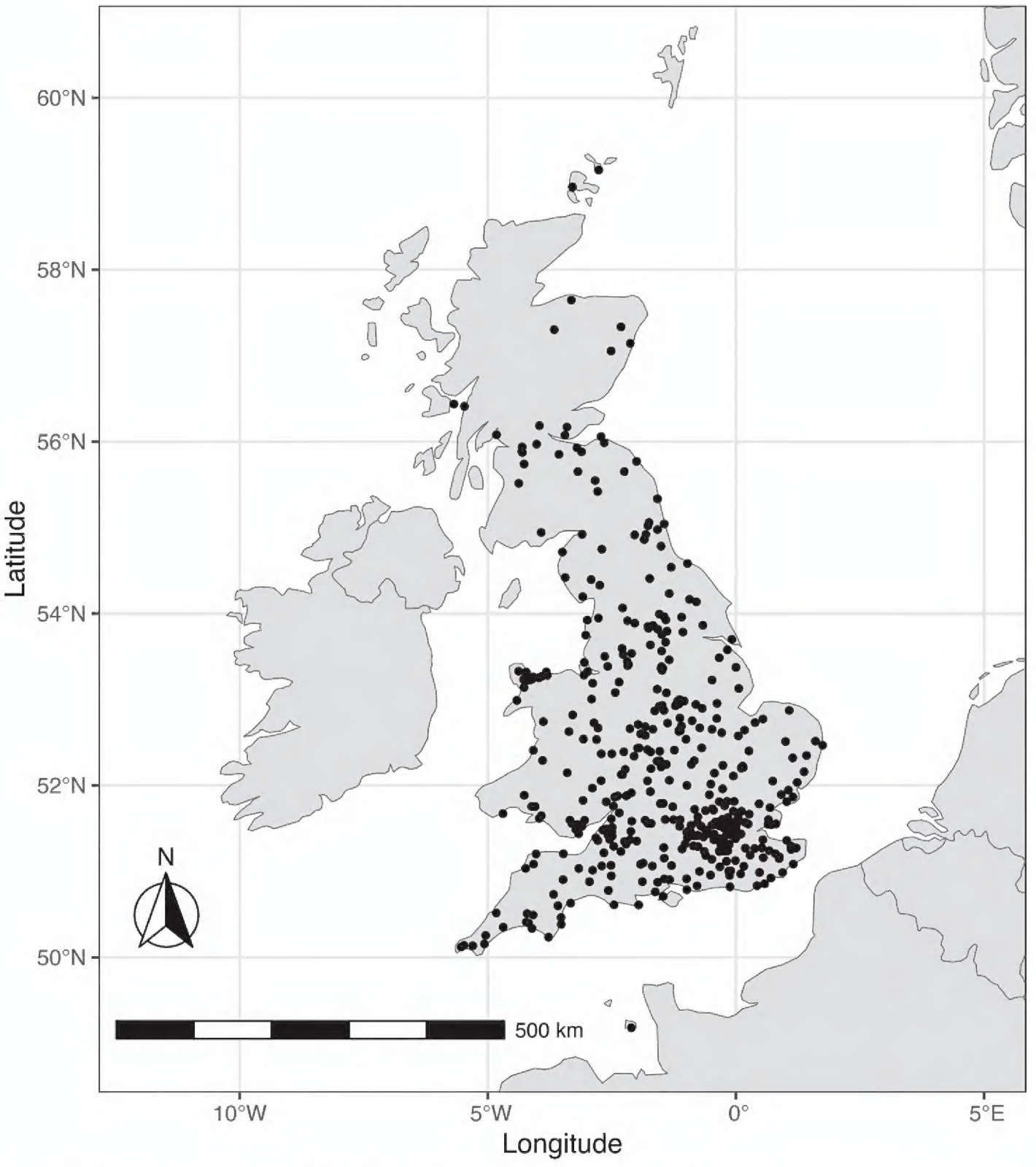

Figure 2. Location of the gardeners [n = 558] who participated in the scoping and Chelsea surveys.

estimated at 0.849 (95% CI: 0.825–0.873) (Fig. 3b, c). This level of SC suggests that for every 6–8 additional gardeners, an additional taxon would be added (each additional gardener surveyed (beyond 558) would add an additional 0.127–0.175 species to the total). Extrapolation to twice the number of survey responses (Fig. 3) gives an estimated 95% CI for species richness of 291.04–353.72 and SC = 0.907 (95% CI: 0.883–0.931).

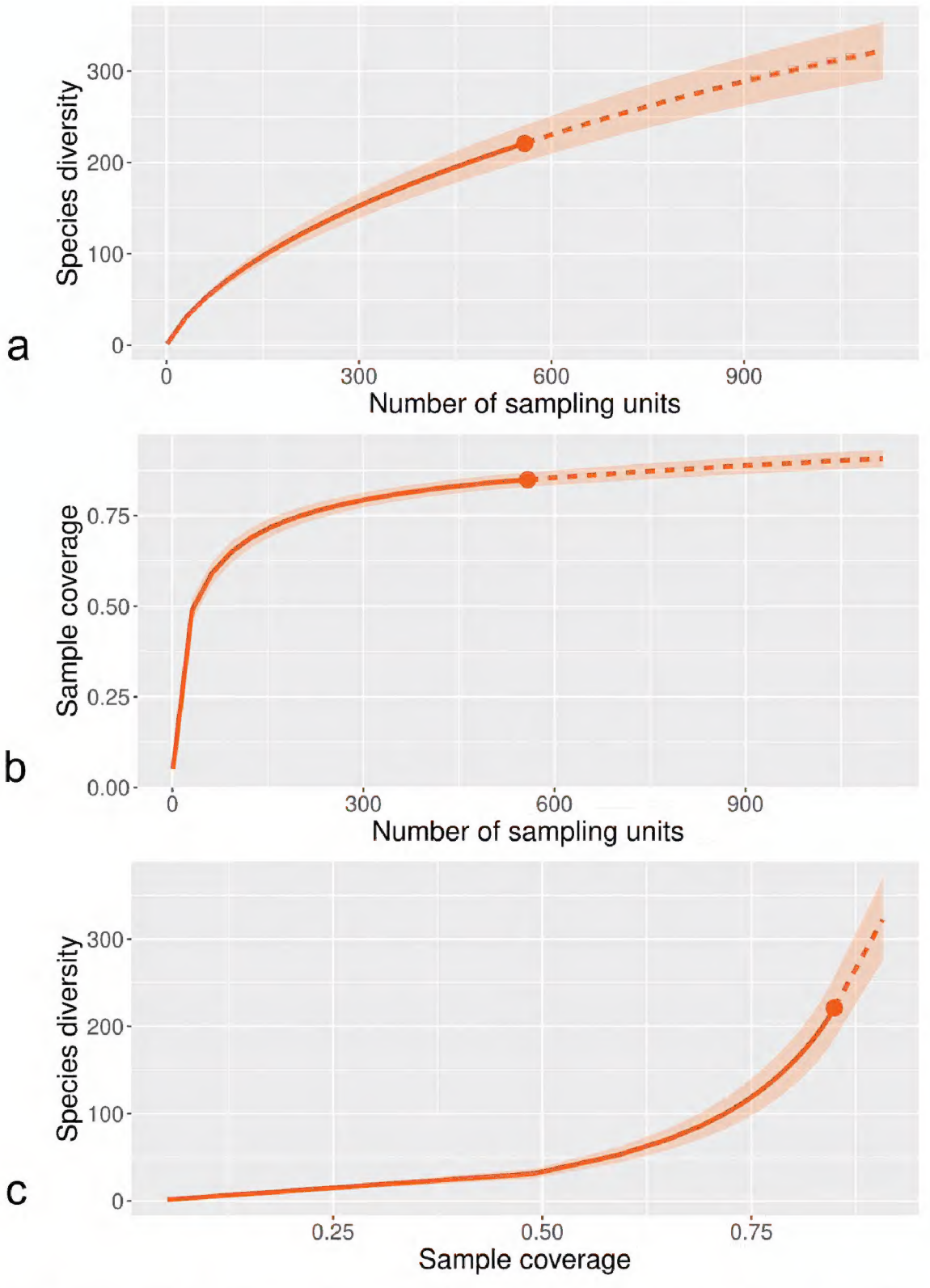

Figure 3. Rarefaction (solid lines) and extrapolation (dashed lines) curves for species richness of potentially invasive plants based on incidence data from gardens. Panel **a** species accumulation curve (species richness with increasing sample number). Panel **b** sample completeness curve (sample coverage with increasing sample number). Panel **c** coverage-based sampling curve (species richness with increasing sample coverage). Shaded areas = 95% confidence intervals (based on 100 bootstrap replications). Number of sampling units = number of gardens. Sample coverage = proportion of the predicted total number of (invasive) species. Solid dot = end of observed data from surveys.

Table 1. The most commonly reported plants (by ≥ 5 gardeners) with N showing number of reports (cultivars are not separated). Statuses (matching Fig. 1): a cell with beige shading (NN) = **non-native**; a cell with light orange shading (S) = **survivor**; a cell with orange shading (N) = **naturalised**; a cell with red shading (I) = **invasive**; with – meaning no record. Statuses from Stace and Crawley (2015) shown as APs for "*Alien Plants*". GB = Great Britain (England, Scotland and Wales), IE = Ireland and Northern Ireland, and BI = British Isles (i.e., GB, IE, the Channel Islands and the Isle of Man). Global invasive status lists countries (excluding GB and IE) where the taxa is listed as invasive in the GRIIS Country Compendium (using alpha-2 codes of the according to the ISO 3166 standard). The number of reports (as of November 18th 2023) via Plant Alert (BSBI 2023) are also shown.

Scientific name	N		Domestic status					Global invasive status (GRISS)
			BI	GB		IE		
	This study	Plant Alert	APs	GloNAF	GRIIS	GloNAF	GRIIS	
Arum italicum Mill. subsp. *italicum*[1]	5	–	N	N	NN	N	NN	AR, NZ, US
Euphorbia cyparissias L.	5	2	N	N	NN	N	NN	EE, LT, NO, US
Fallopia baldschuanica (Regel) Holub	5	6	S	N	I	N	NN	BG, CZ, NL, PT
Geranium nodosum L.	5	3	N	N	NN	N	–	–
Symphoricarpos albus (L.) S.F.Blake[2]	5	9	I	N	I	N	NN	CZ, DK, NL, NO, RU, SE
Parthenocissus quinquefolia (L.) Planch.	6	2	N	N	I	N	NN	BA, HR, CU, CZ, NO, RO, RU, SI, SE
Rosa rugosa Thunb.	6	2	I	N	I	N	I	DK, EE, FI, DE, LV, LT, NL, NO, RU, SE, US
Vinca minor L.	6	1	I	N	I	N	NN	EE, LT, NO, RU, SE, US
Leycesteria formosa Wall.	7	23	N	N	NN	N	NN	NZ
Vinca major L.	7	4	N	N	NN	N	NN	AR, CA, JP, KE, NZ, ZA, US
Reynoutria japonica Houtt. syn. *Fallopia japonica* (Houtt.) Ronse Decr.	8	31	I	N	I	N	I	BY, BA, CA, HR, CZ, DK, EE, FI, FR, IT, LI, LU, ME, NL, NZ, NO, PL, PT, RO, RU, SK, SE, CH, US
Impatiens glandulifera Royle	9	34	I	N	I	N	I	AT, BY, BA, CA, HR, CZ, DK, EE, FI, FR, IT, LV, LI, LT, LU, NL, NZ, NO, RU, SK, SI, SE, CH, US
Allium triquetrum L.	10	16	I	N	NN	N	NN	NZ, ZA
Erigeron karvinskianus DC.	10	8	N	N	NN	N	NN	CL, IN, IT, JP, MU, NP, NZ, TZ, ZM, ZW
Euphorbia amygdaloides Lam. subsp. *robbiae* (Turrill) Stace	10	3	N	N	NN	N	NN	–
Lysimachia ciliata L.	10	1[7]	N	N	NN	–	NN	–
Pilosella aurantiaca (L.) F.W.Schultz & Sch.Bip.[3]	10	15	N	N	NN	N	NN	CA, JP, KG, NZ, NO
Centranthus ruber (L.) DC.[4]	11	9	I	N	NN	N	NN	ZA, US
Symphyotrichum novi-belgii (L.) G.L.Nesom syn. *Aster novi-belgii* L.	11	–	N	N	NN	N	NN	AT, BY, BG, CZ, DE, JP, LT, ME, SK, SE
Aegopodium podagraria L.	12	5	I	N	NN	N	NN	US

Scientific name	N		Domestic status					Global invasive status (GRISS)
			BI	GB		IE		
	This study	Plant Alert	APs	GloNAF	GRIIS	GloNAF	GRIIS	
Houttuynia cordata Thunb.	12	15	N	N	NN	–	–	NL, NZ, US
Soleirolia soleirolii (Req.) Dandy syn. *Helxine soleirolii* Req.	14	8	N	N	NN	N	NN	–
Pentaglottis sempervirens (L.) Tausch ex L.H.Bailey	16	25	I	N	I	–	NN	US
Buddleja davidii Franch.	21	7[8]	I	N	I	N	NN	AR, BA, BG, CA, CZ, DK, FR, IN, IT, JP, LI, NL, NZ, CH, US
Lamium galeobdolon (L.) Crantz subsp. *argentatum* (Smejkal) J.Duvign.	21	11[9]	N	N	–	N	–	CZ
Verbena bonariensis L.	26	8	N	–	NN	–	–	ET, FJ, JP, KE, RW, ZA, TZ, US
Hyacinthoides hispanica (Mill.) Rothm.[5]	29	1[10]	N	N	NN	N	I	US
Alchemilla mollis (Buser) Rothm.	79	6	N	N	I	N	NN	NL, NO, SE, US
Crocosmia × *crocosmiiflora* (Lemoine) N.E.Br.[6]	82	7[11]	I	N	–	N	NN	BR, JP, NZ, PG, US
Anemone × *hybrida* Paxton "Japanese anemone" *s. l.*	86	17[12]	S	–	–	–	NN	–

Included as: [1]*A. italicum* Mill. in GloNAF; [2]*Symphoricarpos albus* (L.) C.Koch in GRISS; [3]*Pilosella aurantiaca* subsp. *aurantiaca* syn. *Hieracium aurantiacum* L. in GRISS for CA and NO; [4]*C. ruber* (All.) Lam. & DC. in GRISS for GB and as *C. ruber* DC. for US; [5]gardeners often mistakenly refer to bluebells grown in gardens as *Hyacinthoides hispanica* or using the vernacular name 'Spanish bluebell' (see Discussion also); [6]included as *Crocosmia crocosmiiflora* (Nicholson) N.E.Br. in GRISS for BR, JP, NZ, PG and the US. [7]Specifically *Lysimachia ciliata* 'Firecracker'; [8]including *B. davidii* 'Black Knight'; [9]included as *Lamiastrum galeobdolon* subsp. *argentatum* (Smejkal) Stace; [10]with an additional three treated as *Hyacinthoides hispanica* agg.; [11]included as records of *Crocosmia* Planch.;[12]including one record of *Anemone* × *hybrida* 'September Charm'.

The most commonly reported taxa (by ≥ 5 gardeners) are shown in Table 1 along with their domestic status, and invasive status globally. Table 1 also includes Plant Alert results (BSBI 2023) as of November 18th 2023 for the respective data.

All taxa in Table 1 are neophytes except for *Aegopodium podagraria* and *Vinca minor* which are archaeophytes (Stace and Crawley 2015). The 251 reported taxa included 5 casuals and 13 survivors (two of which are listed in Table 1) as listed in Stace and Crawley (2015). See Suppl. material 2, for full list.

Discussion

Citizen science has great potential to improve our understanding of invasive species (Johnson et al. 2020) especially in identifying invasive potential (e.g. Dehnen-Schmutz and Conroy 2018). It also has the added benefit of being an opportunity for public

engagement and science communication, informing participants about issues (Miller-Rushing et al. 2012; Tweddle et al. 2012) such as invasive species (Hulme et al. 2017). The focus here is on a citizen science approach to identify future invaders.

Shortlist of future invaders

Ornamentals reported by ≥ 5 gardeners (Table 1) are prioritised here to generate a shortlist. None of the taxa in Table 1 were included in the green list of Dehnen-Schmutz (2011). Although Table 1 does not include any species not known to have escaped gardens in GB or Ireland (Stace and Crawley 2015), it does include two survivors. One of which, *Anemone* × *hybrida*, was the most reported but it has no invasive status globally (Pagad et al. 2022). It was also the joint most frequently reported in Dehnen-Schmutz and Conroy (2018) with six reports, although reported in their study as *Anemone scabiosa* H.Lév. & Vaniot.

Of the reported taxa which have already escaped gardens in GB and/or Ireland but are not yet invasive (Table 1) it is important to focus on those with an invasive status globally (Pagad et al. 2022) as shown in Fig. 1. This gives a shortlist of nine ornamentals: *Arum italicum* subsp. *italicum*, *Erigeron karvinskianus*, *Euphorbia cyparissias*, *Houttuynia cordata*, *Lamium galeobdolon* subsp. *argentatum* (see note below on data sources), *Leycesteria formosa*, *Pilosella aurantiaca*. *Symphyotrichum novi-belgii*, and *Verbena bonariensis*. It is also worth noting, that of the reported plants (Table 1) considered invasive, *Crocosmia* × *crocosmiiflora*, *Hyacinthoides hispanica* were the most frequently reported in Dehnen-Schmutz and Conroy (2018) with six reports each (jointly with *Anemone scabiosa* and *L. galeobdolon* subsp. *argentatum*). Of the shortlisted ornamentals, the following are also listed as the most frequently reported via Plant Alert (2023) as of November 18th 2023: *E. karvinskianus*, *H. cordata*, *L. galeobdolon* subsp. *argentatum*, *L. formosa*, *P. aurantiaca* and *V. bonariensis*.

One problem with prioritising is the differences in status between data sources. For example, as is the case with *Fallopia baldschuanica* (Table 1) and *Lamium galeobdolon* subsp. *argentatum* is arguably already invasive and is listed in Schedule 9 of the Wildlife and Countryside Act which applies in Great Britain. Critically, none of the shortlisted taxa or those listed in Table 1 – except for *Akebia quinata* – were identified during the most recent horizon scanning process for GB because they were beyond the scope of the exercise; e.g. they were already present in the wild (Roy et al. 2019). The approach here is therefore effective in addressing the gap in the identification of potentially invasive ornamentals.

Based on the trajectory of the species accumulation in the survey data (Fig. 3) we suggest that there may be a significant number of additional future invaders that were not reported. This trend, shown in Fig. 3, is similar to that found by Thompson et al. (2003) (albeit of quadrant data not from a survey). Extrapolation from our data suggests that the number of reported species could increase by approximately 1 for every additional 5–8 gardeners surveyed. Very tentatively, the species accumulation curve appears to approach an asymptote at 350–400 species. However, this estimation requires caution as we note it may be a consequence of limiting the total number of

species recorded by each gardener to a maximum of three. This necessarily increases the number of observations required to reach sampling saturation (SC = 1). For more accurate estimation in future surveys, we recommend allowing the observer to enter as many species as they wish (as is now the case with Plant Alert).

Native ornamentals

Native species were removed because they cannot be considered invasive *sensu stricto*. However, there were 169 reports of native species with the most reported species being: *Hedera helix* L. [n = 24], *Carex pendula* Huds. [n = 22], and *Convallaria majalis* L. [n = 10]. This is also a factor with Plant Alert, e.g. with nine reports of *C. pendula* as of November 18th 2019 (BSBI 2023). This raises two important points: 1) the idea of 'cryptic invasions'; and 2) how gardeners understand the term 'invasive'. Firstly, cryptic invasions (Novak 2011) have an impact on native genetic diversity (see Morais and Reichard 2018) with an increasing number of hybrids recorded in Britain and Ireland (Stace et al. 2015) and due to the introduction of non-native genotypes. For example, six different cultivars of native species were reported including *Hedera helix* 'Ivalace' [n = 1]. Secondly, the reports of native species suggest gardeners conflate the term 'invasive' with garden weeds and 'thugs' (Jones et al. 2024). *C. pendula* is a good example of being native but widely considered a weed or 'thug' in gardens (e.g. RHS 2021a), and is even described in Stace and Crawley (2015, 468) as an *"invasive native"*. Conversely, *Geranium nodosum* (Table 1) has no invasive status globally (Pagad et al. 2022) but could be considered by many gardeners to be a weed. This possible conflation of terms has implications for this approach (see below).

Limitations and improving the approach

Dehnen-Schmutz and Conroy (2018) found two limitations to their approach: 1) difficulty with identification skills (see also Johnson et al. (2020)); and 2) motivation of participants. Our study differs from that of Dehnen-Schmutz and Conroy (2018) by targeting gardeners rather than botanists. Their argument was that botanists (mainly members of the Botanical Society for Britain and Ireland) would have better identification skills, but gardeners are arguably more familiar with ornamentals grown in gardens. Furthermore, it is estimated that there are 30 million gardeners in Britain (RHS 2021b), compared to around 3,400 members of the Botanical Society of Britain and Ireland (BSBI 2022), which is a much better opportunity for recruiting participants. This study suggests gardeners are very interested in the issue of invasive species and their role in identifying future invaders. The main limitation in surveys appears to be in the distinction between an invasive – or potentially invasive – species and garden weeds or 'thugs'; specifically in how gardeners understand the term 'invasive' (Jones et al. 2024). This should therefore be explicitly explained before asking gardeners to report future invaders such as by providing a definition or multiple-choice question. An additional consideration is that, thanks to the efforts of gardeners, garden ornamentals

often grow outside the core niche of their native distribution (Yesson and Culham 2006). Hence, species that are thriving inside gardens, and potentially taking over these highly managed spaces, may not be as successful in the wild. Also, there is a degree of uncertainty when asking gardeners to report through a survey due to challenges in identification. For example, bluebells grown in gardens are likely to be *Hyacinthoides* × *massartiana* Geerinck rather than *H. hispanica* (Ruhsam et al. 2023) with the latter being uncommon in gardens and rarely escape into the wild (Rumsey 2023). However, gardeners often refer to them as *H. hispanica* or by using the vernacular name 'Spanish bluebell'. There can also be nomenclature problems such as with the vernacular name 'Japanese anemone' which is applied to several scientific names including *Anemone hupehensis* (Lemoine) Lemoine and *A.* × *hybrida* (Cubey et al. 2022), and under '*A. scabiosa*' (Dehnen-Schmutz and Conroy 2018). Using a drop-down question which searches for a taxon (as is the case now with Plant Alert) does not necessarily address these challenges because it still relies on gardeners identifying the correct taxon in their report. It does, however, reduce the number of reports being discarded through data cleaning.

This approach, if improved as suggested above and by allowing gardeners to report as many species as they wish, could be adopted as a form of horizon scanning for identifying future invaders even if it is not looking at 'door knocker' species (Seebens et al. 2018). This gives the opportunity to prioritise the approximately 70,000 ornamentals (Cubey et al. 2022) available for sale in the UK. This could also be extended beyond individual gardeners as the target audience (as in this study) to better engage with a wider range of gardeners and landscapers, such as those working in public or botanic gardens and in residential areas. This would build on work already done in the Czech Republic (Kutlvašr et al. 2019, 2020), which could be replicated in Britain and Ireland, to ensure selection of ornamentals do not include future invaders. Central to the approach is the structured scheme for prioritising future invaders (Fig. 1). This is also important for deciding which taxa need the invasive potential to be measured; for example, by adopting a species distribution modelling and/or trait-based approach (e.g. Fournier et al. 2019). This would result in both identifying future invaders and measuring their invasive potential.

Conclusion

Identifying future invaders before they can become invasive in the wild is an important yet challenging issue for invasion science. Gardeners have a crucial role here in being the 'first contact' for reporting ornamentals with invasive potential because ornamental horticulture is a main introduction pathway or source of invasive species globally. By addressing the research question of this study we have shown that data collected by gardeners can be used in a simple yet structured approach with the scheme for prioritising future invaders. This structured scheme is applied here to prioritise species in need of further analysis, such as a risk assessment, and has resulted in a shortlist of nine ornamentals of concern. Importantly, the shortlisted taxa were not identified as potentially

invasive through horizon scanning. Furthermore, the approach has considerable potential for increasing awareness of invasive and potentially invasive ornamentals through engagement with gardeners by notifying them of the ornamentals of concern. This positive feedback loop between gardeners and invasion scientists could help reduce the risk of more ornamentals becoming invasive in the future.

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Supplementary material 1

Scoping survey
Authors: Tomos Siôn Jones, Alastair Culham, Brian John Pickles, John David
Data type: docx
Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.
Link: https://doi.org/10.3897/neobiota.91.110560.suppl1

Supplementary material 2

Full list of reported taxa (cultivars not included) along with a unique ID for each gardener (survey participants)
Authors: Tomos Siôn Jones, Alastair Culham, Brian John Pickles, John David
Data type: csv
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Link: https://doi.org/10.3897/neobiota.91.110560.suppl2